

# Radiative transfer modelling for sun glint correction in marine satellite imagery

Submitted by Susan Barbara Kay to the University of Exeter  
as a thesis for the degree of  
Doctor of Philosophy in Biological Sciences  
In December 2011.

This thesis is available for Library use on the understanding that it is copyright  
material and that no quotation from the thesis may be published without proper  
acknowledgement.

I certify that all material in this thesis which is not my own work has been  
identified and that no material has previously been submitted and approved for  
the award of a degree by this or any other University.

Signature: .....



# Abstract

Remote sensing is a powerful tool for studying the marine environment; however, many images are contaminated by sun glint, the specular reflection of light from the water surface. Improved radiative transfer modelling could lead to better methods for estimating and correcting sunglint. This thesis explores the effect of using detailed numerical models of the sea surface when investigating the transfer of light through the atmosphere-ocean system.

New numerical realisations that model both the shape and slope of the sea surface have been created; these contrast with existing radiative transfer models, where the air-water interface has slope but not elevation. Surface realisations including features on a scale from 3 mm to 200 m were created by a Fourier synthesis method, using up to date spectra of the wind-blown sea surface. The surfaces had mean square slopes and elevation variances in line with those of observed seas, for wind speeds up to  $15 \text{ m s}^{-1}$ . Ray-tracing using the new surfaces gave estimates of reflected radiance that were similar to those made using slope statistics methods, but significantly different in 41% of cases tested. The mean difference in the reflected radiance at these points was 19%, median 7%. Elevation-based surfaces give increased sideways scattering and reduced forward scattering of light incident on the sea surface.

The elevation-based models have been applied to estimate pixel-pixel variation in ocean colour imagery and to simulate scenes viewed by three types of sensor. The simulations correctly estimated the size and position of the glint zone. Simulations of two ocean colour images gave a lower peak reflectance than the original values, but higher reflectance at the edge of the glint zone. The use of the simulation to test glint correction methods has been demonstrated, as have global Monte Carlo techniques for investigating sensitivity and uncertainty in sun glint correction.

This work has shown that elevation-based sea surface models can be created and tested using readily-available computer hardware. The new model can be used to simulate glint in a variety of situations, giving a tool for testing glint correction methods. It could also be used for glint correction directly, by predicting the level of sun glint in a given set of conditions.

# Acknowledgments

I would like to thank all my supervisors for their advice and support: John Hedley for an endless flow of good ideas and constructive criticism, and for his patience in explaining PlanarRad more than a few times; Sam Lavender for big questions that led in fruitful directions; Alex Nimmo-Smith for valuable input on the sea surface and access to useful resources at the University of Plymouth; Peter Mumby for giving me the essential link to the University of Exeter, even via Brisbane – distance is no object these days.

This work was supported by Great Western Research, studentship number 363, with ARGANS Ltd as the industry partner. I am grateful to both organisations for their financial support.

My thanks go to colleagues at ARGANS and Exeter, whose questions and information provoked many useful thoughts and ideas. And thanks also to family and friends who let me look at waves for as long as I wanted.

## Image and data acknowledgements

MERIS data, Figs. 1.1(a), 2.4, 5.3, 6.4 provided by the European Space Agency.

IKONOS data, Figs. 1.1(b), 2.7 ©2003, European Space Imaging GmbH, all rights reserved.

CASI images, Figs. 1.1(c), 2.6 based on digital spatial data licensed from the Natural Environment Research Council ©NERC 1998.

# Contents

<b>Contents</b>	<b>5</b>
<b>List of Figures</b>	<b>9</b>
<b>List of Tables</b>	<b>14</b>
<b>Definitions</b>	<b>16</b>
0.1 Abbreviations used in the text . . . . .	16
0.2 List of remote sensing instruments referred to in the text . . . . .	18
0.3 List of symbols used in the text . . . . .	20
<b>1 Introduction</b>	<b>23</b>
1.1 The problem of sun glint . . . . .	24
1.2 Modelling the air-sea interface and the motivation for the current work	27
1.3 Summary of work presented in this thesis . . . . .	28
1.4 Key findings . . . . .	28
<b>2 Sun glint correction: theoretical background and a review of current methods</b>	<b>30</b>
2.1 Introduction . . . . .	30
2.2 Theoretical background . . . . .	30
2.2.1 Radiative transfer processes . . . . .	31
2.2.2 Geometric estimation and prediction of sun glint . . . . .	34
2.2.3 Avoidance of sun glint . . . . .	37
2.3 Summary of current glint correction techniques . . . . .	38

2.4	Correction methods based on statistical models of the sea surface state . . . . .	42
2.4.1	The Cox and Munk statistical model of the sea surface state . . . . .	42
2.4.2	The SeaWiFS correction method . . . . .	46
2.4.3	Other methods using sea surface slope statistics: MERIS and GLI . . . . .	49
2.4.4	Limitations of the SeaWiFS and MERIS schemes . . . . .	52
2.4.5	New methods based on neural networks . . . . .	53
2.5	Methods for shallow water, high resolution images . . . . .	55
2.5.1	Theoretical background . . . . .	55
2.5.2	The method of Hedley et al. (2005); Figs. 2.6(b), 2.7(b). . . . .	56
2.5.3	The method of Lyzenga et al. (2006); Figs. 2.6(c), 2.7(c) . . . . .	57
2.5.4	The method of Goodman et al. (2008); Figs. 2.6(d), 2.7(d) . . . . .	58
2.5.5	The method of Kutser et al. (2009); Fig. 2.6(e) . . . . .	59
2.5.6	Comments on the methods . . . . .	62
2.5.7	Limitations of these methods . . . . .	64
2.6	Crossover methods . . . . .	65
2.7	Wavelengths outside the visible and NIR . . . . .	66
2.8	Useful glint . . . . .	67
2.9	Summary and prospects for further development . . . . .	67
<b>3</b>	<b>Describing and modelling the sea surface</b>	<b>69</b>
3.1	Introduction . . . . .	69
3.2	Ocean waves and the sea surface spectrum . . . . .	69
3.2.1	Processes driving the development of sea surface waves . . . . .	70
3.2.2	Statistical description of wave fields . . . . .	73
3.2.3	Observational data on sea surface waves . . . . .	76
3.2.4	Development of sea wave spectra . . . . .	79
3.2.4.1	The directional spreading function . . . . .	83
3.2.4.2	The effect of wave modulation . . . . .	85
3.3	The air-water interface in radiative transfer models . . . . .	87

3.4	Summary . . . . .	90
<b>4</b>	<b>Model creation and testing</b>	<b>91</b>
4.1	Introduction . . . . .	91
4.2	Choice of spectrum for surface construction . . . . .	92
4.3	Creation of surface realisations from a wave spectrum . . . . .	94
4.4	Validation of the realised surfaces . . . . .	97
4.5	Integration into a ray-tracing model . . . . .	99
4.6	Results and discussion . . . . .	103
4.6.1	Comparison to slope-statistics model . . . . .	103
4.7	Summary . . . . .	107
<b>5</b>	<b>Applications of the model</b>	<b>108</b>
5.1	Introduction . . . . .	108
5.2	Pixel-pixel variation in imagery . . . . .	108
5.3	Creating scene simulations . . . . .	110
5.3.1	Method of setting up a scene simulation . . . . .	111
5.4	Case study 1: simulation of two MERIS images . . . . .	114
5.4.1	Details of the simulation method . . . . .	114
5.4.2	Results from the standard model . . . . .	118
5.4.3	The effect of sky glint . . . . .	122
5.4.4	Results using a slope-statistics sea surface . . . . .	123
5.4.5	The effect of changing the parameters used to calculate the glint reflectance . . . . .	125
5.4.6	Comparison of the atmosphere models . . . . .	127
5.4.7	The effect of changing IOP values . . . . .	130
5.4.8	The effect of multiple scattering at the surface . . . . .	132
5.4.9	The effect of angular resolution . . . . .	132
5.4.10	Discussion and conclusions . . . . .	134
5.4.11	Additional Figures . . . . .	136
5.5	Case study 2: CASI image with cross-track glint . . . . .	139

5.5.1	Details of the simulation method . . . . .	139
5.5.2	Results . . . . .	141
5.5.3	Discussion and conclusions . . . . .	143
5.6	Case study 3: a nadir-viewed image with wave-top glint . . . . .	146
5.6.1	Details of the simulation method . . . . .	146
5.6.2	Results . . . . .	148
5.6.3	Discussion and conclusions . . . . .	151
5.7	Summary . . . . .	153
<b>6</b>	<b>Sensitivity and uncertainty analysis in sun glint correction</b>	<b>155</b>
6.1	Introduction . . . . .	155
6.2	Quality indicators for Earth Observation . . . . .	155
6.3	Uncertainty estimation for the Ocean and Land Colour Instrument .	156
6.3.1	Sensitivity analysis . . . . .	157
6.3.2	Case study of uncertainty effects in imagery . . . . .	161
6.3.3	Extension to all input values . . . . .	163
6.4	Sensitivity and uncertainty issues for the model developed in this work	167
6.4.1	Methods . . . . .	167
6.4.2	Results and discussion . . . . .	169
6.4.3	Conclusions . . . . .	176
6.5	Summary . . . . .	176
<b>7</b>	<b>Discussion and further work</b>	<b>178</b>
<b>8</b>	<b>Conclusion</b>	<b>182</b>
	<b>Bibliography</b>	<b>184</b>